ANALYSIS OF MULTIPLE SCATTERING
OF HIGHLY SCATTERING OPTICAL TRANSMISSION POLYMER

Takamitsu Okumura, Takeshi Ishikawa, Akihiro Tagaya, and Yasuhiro Koike

*Faculty of Science and Technology, Keio University

/ **ERATO Koike Photonics Polymer Project, Japan Science and Technology Corporation

*3-14-1, Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan

/ **E-building, K^2 Town-Campus, 144-8 Ogura, Saiwai-ku, Kawasaki 212-0954, Japan

Phone: *+81-45-566-1593   Fax: *+81-45-562-7373

E-mail: t_okumura@appi.keio.ac.jp

1. Abstract

We have proposed the highly scattering optical transmission (HSOT) polymer, and have applied it to a high efficiency backlight for liquid crystal displays (LCDs). It is an important candidate for new various optical devices.   In the present work, the multiple scattering modeling simulation has been developed.   Also the effect of adjacent particles inside the HSOT polymer is demonstrated.   It follows that the numerical calculation considering the effect of adjacent particles has precisely reproduced multiple scattering phenomena inside the HSOT polymer.   This indicates that an optimal design of the illuminating property of HSOT polymer can be conducted by applying the multiple scattering analysis developed in this paper.

2. Introduction

The HSOT polymer is a novel illuminating medium, where an incident light is converted into homogeneous scattered light efficiently due to the internal heterogeneous structures.   An LCD backlight using the HSOT polymer, which showed twice the brightness of the conventional transparent one, has been produced.[1-3]   In order to use the HSOT polymer as a new optical source, one must optimize a number of issues, including those related to shapes, materials, and internal particle conditions.   The analyzing method in the present work enables us to calculate the illuminating property of the HSOT polymer quantitatively using the multiple scattering modeling simulation.   The main objective of this paper is to investigate the behavior of multiple scattering characteristics inside the HSOT polymer and to put on the basis for the optimal design method of a novel lighting source using the HSOT polymer.

3. Multiple Scattering Modeling Simulation

A multiple scattering phenomenon inside the HSOT polymer is theoretically analyzed by the ray-tracing simulation program using the Monte Carlo method based on Mie scattering theory[4].   It is widely recognized that the Monte Carlo method allows us to resolve a number of physical issues with no immediate probabilistic interpretation.   In this simulation program, a light scattering intensity profile and scattering efficiency of a single particle can be calculated by Mie scattering theory as follows:

$$I(\alpha, m, \theta) = \lambda^2 (i_1 + i_2) / 8\pi^2 \qquad (1)$$

$$K(\alpha, m) = \left(\frac{\lambda^2}{2\pi^2 r^2}\right) \sum_{v=1}^{\alpha} (2v+1)\left\{|a_v|^2 + |b_v|^2\right\} \qquad (2)$$

$$i_1 = \left|\sum_{v=1}^{\infty} \frac{2v+1}{v(v+1)} \left\{ a_v \frac{P_v^1(\cos\theta)}{\sin\theta} + b_v \frac{dP_v^1(\cos\theta)}{d\theta} \right\}\right|^2$$

$$i_2 = \left|\sum_{v=1}^{\infty} \frac{2v+1}{v(v+1)} \left\{ b_v \frac{P_v^1(\cos\theta)}{\sin\theta} + a_v \frac{dP_v^1(\cos\theta)}{d\theta} \right\}\right|^2 \qquad (3)$$

$$a_v = \frac{\psi_v'(m\alpha)\psi_v(\alpha) - m\psi_v(m\alpha)\psi_v'(\alpha)}{\psi_v'(m\alpha)\zeta_v(\alpha) - m\psi_v(m\alpha)\zeta_v'(\alpha)}$$

$$b_v = \frac{m\psi_v'(m\alpha)\psi_v(\alpha) - \psi_v(m\alpha)\psi_v'(\alpha)}{m\psi_v'(m\alpha)\zeta_v(\alpha) - \psi_v(m\alpha)\zeta_v'(\alpha)} \qquad (4)$$

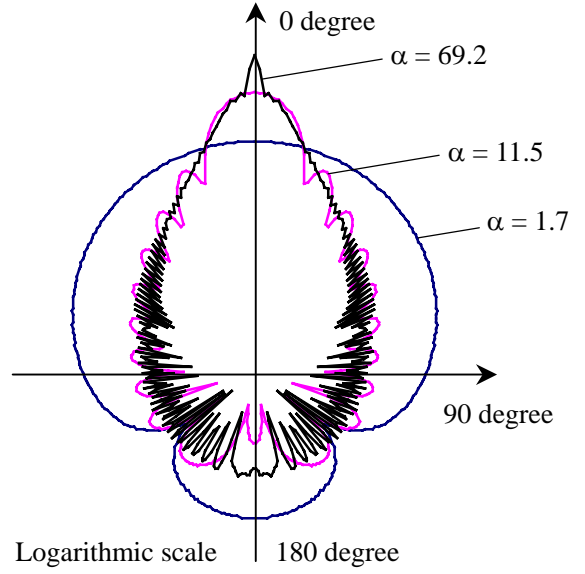$$\alpha = 2\pi r / \lambda \qquad (5)$$

$$m = n_s / n_m \qquad (6)$$

Figure 1　Calculated single scattering profiles by Mie scattering theory.
　Size parameters : α = 1.7, 11.5, 69.2
　Relative refractive index : m = 0.961

where $I(\alpha, m, \theta)$ and $K(\alpha, m)$ is the scattering intensity and scattering efficiency, α is the size parameter, m is the relative refractive index between particle (n_s) and matrix (n_m), r is the particle radius, and λ is the wavelength of incident light in the matrix. $P_v^1(\cos\theta)$ is the Legendre polynomial, ψ_v, ζ_v are the first two orders of the Ricatti-Bessel functions. Shown in Figure 1 are the light scattering intensity profile data of a single particle that is to say single scattering profiles. Notice that a forward directional scattering profile becomes predominant with increasing α regarding scattering profiles in forward direction (0-90 degree) and backward direction (90-180 degree).

By the Monte Carlo method, expected photon pass length L and scattering angle θ are defined as follows:

$$\sigma = \pi \int_0^\infty \int_0^\infty r^2 n_a(r) f(\lambda) K(\alpha, m) dr d\lambda \qquad (7)$$

$$L = -\ln(random1) / \sigma \qquad (8)$$

$$F(\theta) = \frac{\int_0^\theta 2\pi\, I(\theta)\sin\theta d\theta}{\int_0^\pi 2\pi\, I(\theta)\sin\theta d\theta} \qquad (9)$$
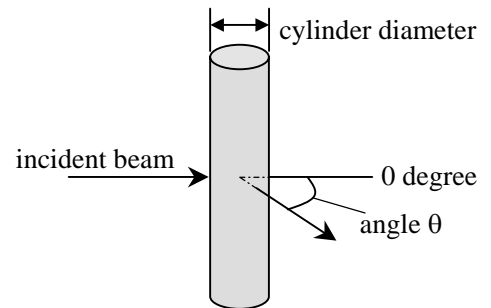
$$\theta = F^{-1}(random2) \qquad (10)$$

Figure 2　A schematic diagram of modeling for multiple scattering of HSOT polymer cylinder.

where σ is the extinction constant, $F(\theta)$ is the probability density distribution function of scattering angle. $n_a(r)$ is the particle concentration, $f(\lambda)$ is the probability distribution function of wavelength, random 1 and 2 are the uniform random numbers generated between 0 to 1, and $I(\theta)$ is scattering intensity profile. A schematic diagram of modeling for multiple scattering of HSOT polymer cylinder is shown in Figure 2.

4. Results and Discussion

A single scattering profile calculated by Mie scattering theory is based on the assumption that there is only one particle as a prerequisite for Mie scattering theory shown in Figure 3 (a), as opposed to the actual scattering property inside the HSOT polymer shown in Figure 3 (b).

Shown in Figure 4 are the data from measurement of scattering profiles of the HSOT polymer cylinder at 633 nm. A commercially available scattering measurement system (Otsuka Electric Co. DLS-7000) is employed. In this experiment, the cylinder diameter is designed in such a way that the average number of scattering points may be approximately from 1.0 to 1.6 calculated by Mie scattering theory. Due to this theoretical assumption, single scattering profiles would be measured as the same one without depending on particle concentration, whereas, as data indicate, measured scattering intensity appears to increase with increasing particle concentration. It follows from this that effects of adjacent particles depending on particle concentration have been observed in measured scattering profiles, as has been considered in the modeling shown in Figure 3.

Figure 3 A schematic diagram of modeling single scattering profiles. (a) is indicative of the Mie scattering theory and (b) is of the HSOT polymer.

It should be also noted that the measured profile of 0.05 wt% particle concentration shown in Figure 4 is in a good agreement with calculated Mie scattering profile. This means that an analysis using Mie scattering theory can be conducted up to such a condition that the calculated distance among adjacent particles is about 130 times as long as the measured wavelength.
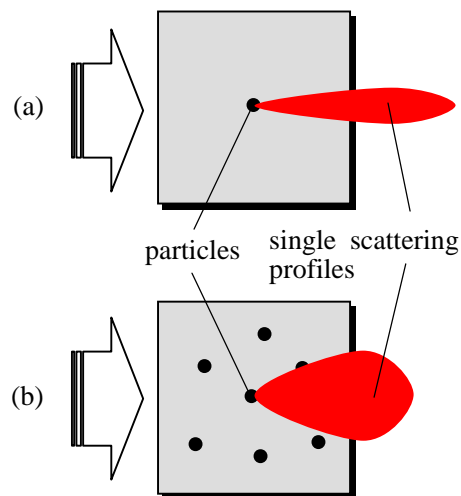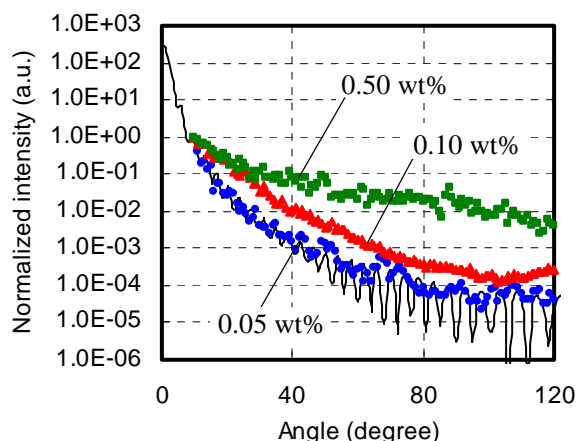

Figure 4 Scattering profile measurements of 1.0 mmφ HSOT polymer cylinder. Vertical axis is normalized at 10 degree. Dotted lines indicate the experimental results, and a solid line is the calculated result by Mie scattering theory.
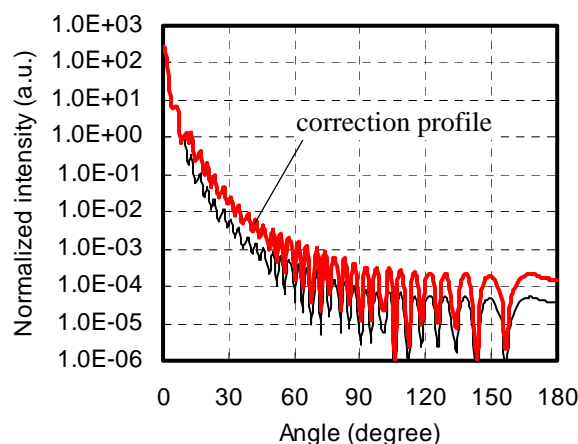

Figure 5 A single scattering profile for the analysis of multiple scattering corrected by measurement profiles. A bold line indicates the correction profile, and a thin line indicates a Mie scattering profile.

In spite of the upper limit of particle concentration for Mie scattering theory, most of the HSOT backlights are of higher particle concentration range from 0.10 to 0.30 wt%.   An experimental correction coefficient was made by the ratio of measured data to 0.05 wt% measured data, which has reproduced the single Mie scattering profile. The resultant correction single scattering profile is shown in Figure 5.

The calculated scattering profiles by multiple scattering modeling simulation are compared to the measurement data as shown in Figure 6.   Notice that a remarkable difference in the calculated profile based on Mie scattering theory has greatly improved in that based on correction single scattering profile, resulting in a very good agreement between the calculated and measurement profiles.   This means that the multiple scattering phenomenon inside the HSOT polymer has been precisely reproduced by the multiple scattering modeling simulation based on the correction profile considering the effects of adjaceint particles which is proposed in this papar.
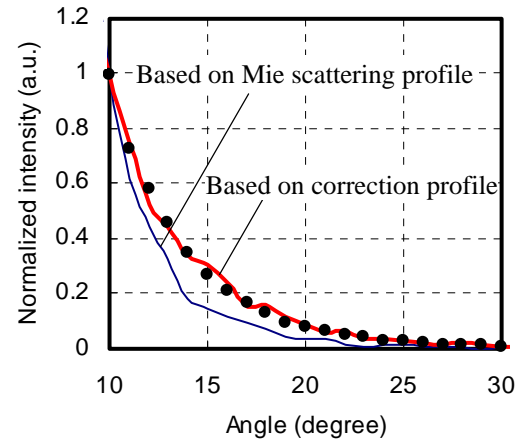

Figure 6   Multiple scattering profiles of 10.0 mmϕ HSOT polymer cylinder. Particle concentration is 0.10 wt%.   Dotted line indicates the measurement data, bold solid lines indicate the calculated profiles.

5. Conclusion

In the present work, numerical calculations by the multiple scattering modeling simulation program have succeeded to reproduce quantitatively the angular dependence of multiple scattering behavior of the HSOT polymer cylinder.   Multiple scattering analysis results have indicated that, due to the effect of adjacent particles over the observed upper limit concentration for Mie scattering theory, single scattering profiles differ depending on the particle concentration, in which one may apply the correction single scattering profile.   This warrants future work of the analysis at a number of wavelengths for a new application for lighting of HSOT polymer. Nonetheless, it is quite noteworthy to say that the improved multiple scattering modeling simulation program allows us to develop the optimal design method for a new lighting instrument using the HSOT polymer if it is applied for white light, and also allows us to open the way for the great advantage of using HSOT polymer for various photonics applications.

6. References

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